Next-Generation Susceptibility MRI Sequences for Brain Imaging: Application to Multiple Sclerosis Biomarkers

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Introduction

Magnetic resonance imaging (MRI) plays a pivotal role in the diagnosis of multiple sclerosis (MS) by enabling non-invasive detection of conventional T2-hyperintense lesions as well as more advanced imaging biomarkers, such as the central vein sign (CVS) and paramagnetic rim lesions (PRL) [1–3]. Given that CVS and PRL are now part of the diagnostic criteria of MS, the use of susceptibility-sensitive MRI sequences is strongly recommended in routine diagnostic MRI evaluation for MS [4].

In our previous MAGNETOM Flash article (↗ Optimized Susceptibility MRI Sequences), we described the utility of an optimized 3D SWI gradient-echo (3D GRE) sequence and a submillimeter T2*-weighted 3D echo planar imaging (3D EPI) sequence for achieving high-confidence detection of CVS and PRL [5]. However, these techniques typically require a scan time of 4 to 6 minutes to achieve clinically interpretable image quality [6–8].

Recent advances in parallel imaging (PI) and deep learning (DL) techniques have significantly transformed MRI, enabling substantial reductions in scan time while improving image quality. In this article, we describe the next-generation susceptibility-sensitive MRI sequences leveraging these recent advances for achieving faster imaging of CVS and PRL at clinical field strengths (e.g., 1.5T and 3T). The goal of these new sequences is to benefit both patients and healthcare providers by shortening examination times, improving patient comfort, and increasing imaging throughput for the diagnostic evaluation of MS.

MRI acquisitions

All cases presented in this article were acquired on 1.5T and 3T MRI scanners (MAGNETOM Sola and MAGNETOM Vida; Siemens Healthineers, Erlangen, Germany) using 20-channel head coils at Cedars-Sinai Medical Center (Los Angeles, CA, USA). Susceptibility-weighted imaging (SWI) and T2*-weighted imaging protocols were optimized to improve visualization of the CVS and PRL while reducing scan time. Scan time reduction was primarily achieved using a research sequence[1] with segmented 3D EPI readout alone or in combination with Generalized Autocalibrating Partially Parallel Acquisitions (GRAPPA) and Controlled Aliasing in Parallel Imaging Results in Higher Acceleration (CAIPIRINHA). Since data undersampling typically results in lower signal-to-noise ratio (SNR) and image resolution, Deep Resolve Boost (DRB) and Deep Resolve Sharp (DRS) were also used during image reconstruction to improve both SNR and image resolution. A total of four imaging protocols are presented here: **(Protocol A)** SWI with 3D EPI readout (SWI-EPI); **(Protocol B)** Fast SWI-EPI with CAIPIRINHA and Deep Resolve; **(Protocol C)** Fast submillimeter isotropic T2*-weighted 3D EPI with CAIPIRINHA and Deep Resolve at 3T, and **(Protocol D)** with GRAPPA and Deep Resolve at 1.5T.

The corresponding sequence parameters are summarized in Table 1.

[1] *Work in progress. The application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

Protocol A: Susceptibility-weighted imaging using 3D EPI (SWI-EPI)

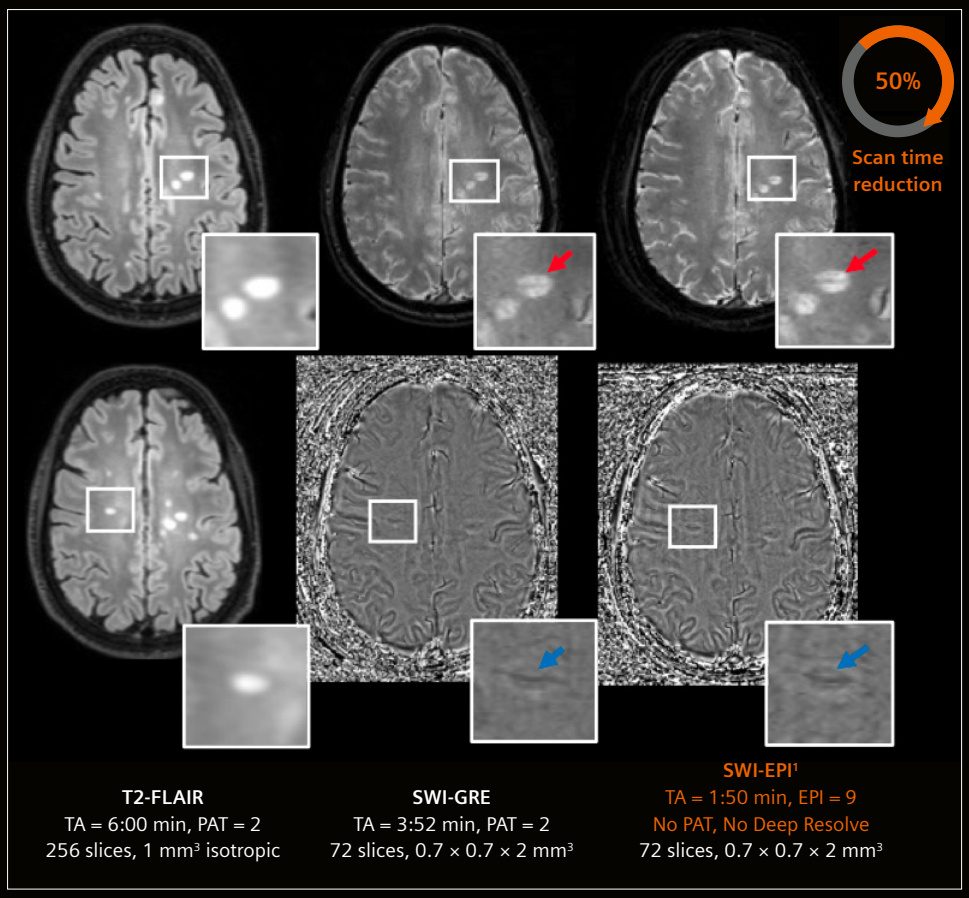
Conventional SWI-GRE can be optimized for CVS detection by reducing the flip angle to decrease T1 weighting, thereby improving lesion conspicuity [5, 9]. This optimization, however, does not reduce the acquisition time, which remains in the 4-minute range. To accelerate this scan, the 3D GRE readout was replaced by a 3D EPI readout. This is an extension of the 3D EPI protocol we published in our previous article [5], without any parallel imaging acceleration but with SWI now available for real-time postprocessing on the scanner console. Using an EPI factor of 9, the SWI-EPI acquisition time is approximately 50% faster than standard SWI-GRE, with a scan time of 1:50 minute instead of 3:59 minutes. Note that this EPI factor minimizes distortion artifacts while maximizing scan time reduction. When comparing SWI-EPI and SWI-GRE magnitude images head-to-head, both provide similar quality and visualization of CVS (Fig. 1, top row). Note that the use of a low flip angle (5°) increases T2* weighting, making brain lesions hyperintense and central veins hypointense, which enables standalone detection of the CVS. Filtered phase images available from the scanner can also be collected and used for the detection of PRL (Fig. 1, bottom row). Both SWI-EPI and SWI-GRE filtered phase images provided similar quality and visualization of PRL.

Protocol B: Fast SWI-EPI with PI and DL reconstruction

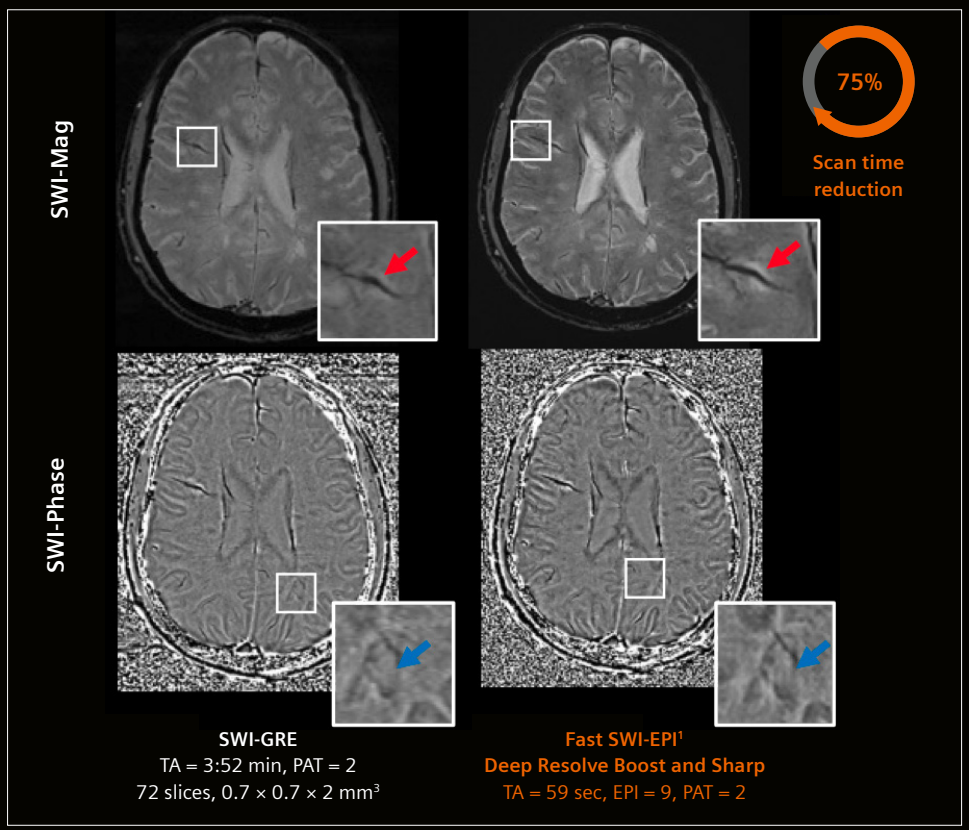
Here, SWI-EPI acquisition was further accelerated with CAIPIRINHA (2 × 2, shift = 1) and reconstructed with Deep Resolve Boost and Deep Resolve Sharp. Deep Resolve Boost suppressed noise amplification and improved SNR, while Deep Resolve Sharp enhanced structural details by increasing spatial resolution. As a result, the acquisition time of Fast SWI-EPI was just 59 seconds, compared to 3:52 minutes for SWI-GRE (75% reduction), without compromising diagnostic image quality or the detection of CVS and PRL (Fig. 2).

Sequence parameters	**Protocol A** SWI-EPI	**Protocol B** Fast SWI-EPI[1]	**Protocol C** Fast T2* 3D-EPI[1] (3T)	**Protocol D** Fast T2* 3D-EPI[1] (1.5T)
TE (ms)	21	21	36	46
TR (ms)	46	46	67	92
FA (deg)	5	5	10	10
In-plane resolution (mm^2)	0.7 × 0.7	0.7 × 0.7	0.65 × 0.65	0.8 × 0.8
Slice thickness (mm)	2	2	0.65	0.8
FOV read (mm)	240	240	250	250
FOV phase (%)	81.3	81.3	81.3	81.3
Number of slices	72	72	256	256
Orientation	Axial	Axial	Sagittal	Sagittal
Parallel imaging (acceleration factor)	None	CAIPIRINHA (1 × 2, shift = 1)	CAIPIRINHA (2 × 2, shift = 1)	GRAPPA (2 × 1)
DL reconstruction	None	DRB and DRS	DRB and DRS	DRB and DRS
EPI factor	9	9	17	13
Bandwidth (Hz/Px)	440	440	394	252
Reconstruction	Magn/Phase	Magn/Phase	Magn/Phase	Magn/Phase
Coil combination	Adaptive combine	Adaptive combine	Adaptive combine	Adaptive combine
Scan time (min:sec)	1:50	0:59	1:30	3:00

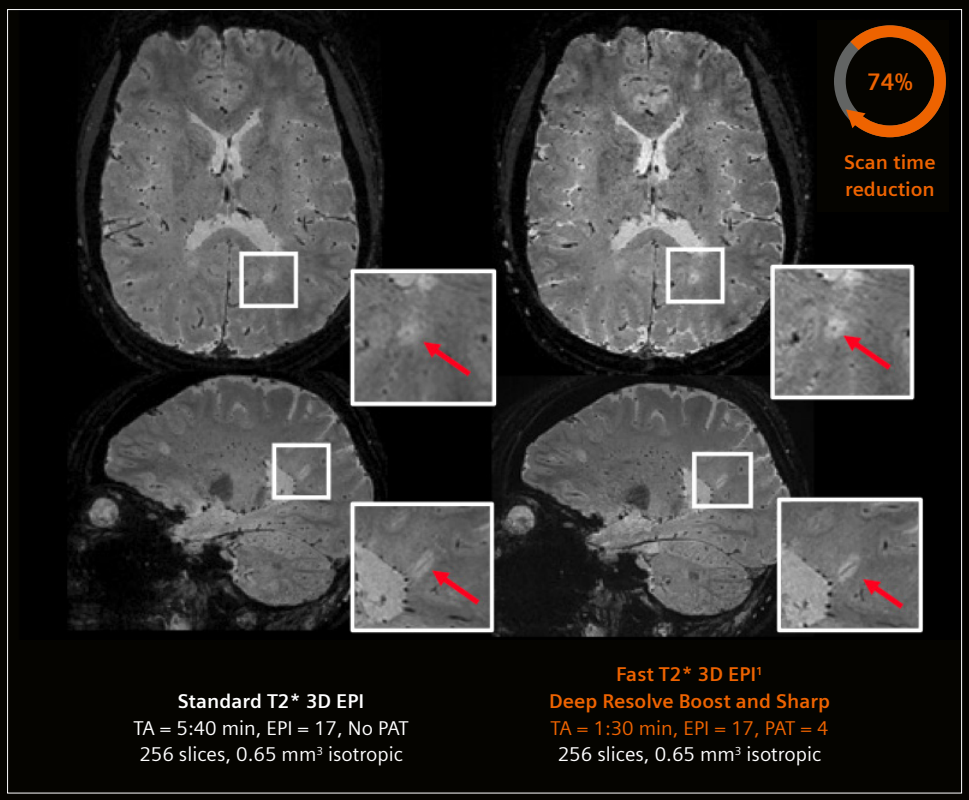
Table 1: Main acquisition parameters of the four proposed MRI protocols



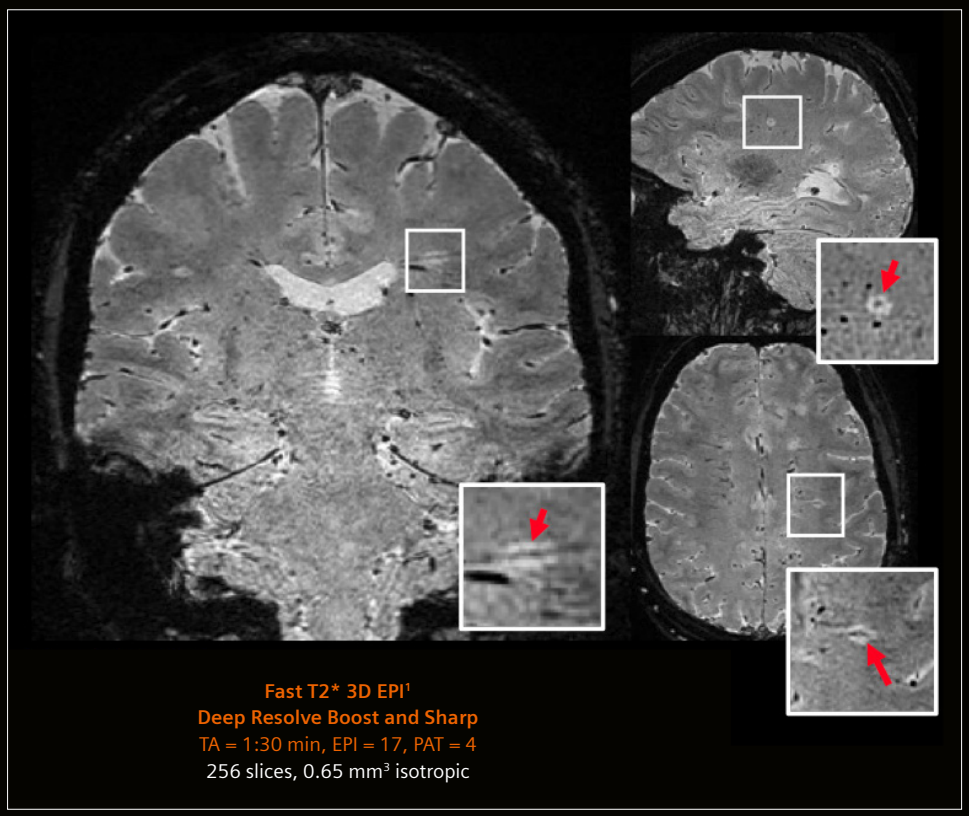
1 Head-to-head comparison of conventional SWI-GRE versus SWI-EPI (Protocol A) acquired in the same MS subject using the same 3T MAGNETOM Vida system. T2-FLAIR images show focal hyperintense lesions in the deep white matter. SWI-EPI provides similar visualization of the Central Vein Sign (CVS) as compared to SWI-GRE (red arrows) while reducing the acquisition time by 50%. Filtered phase images of SWI-GRE and SWI-EPI demonstrate similar visualization of a Paramagnetic Rim Lesion (PRL) with a central vein (blue arrows). For display purposes, the filtered phase images are contrast-inverted so that paramagnetic structures appear hypointense, consistent with the right-handed convention commonly used in the literature [4].



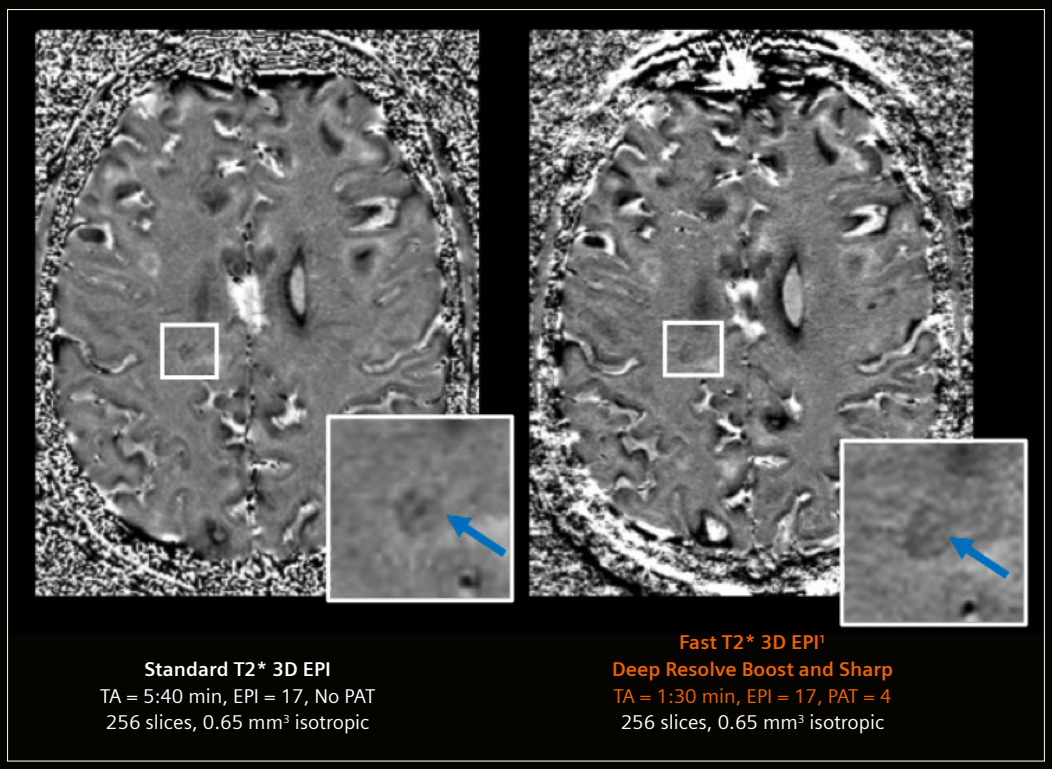
2 Head-to-head comparison of conventional SWI-GRE and Fast SWI-EPI with CAIPIRHINA and Deep Resolve (Protocol B), acquired in the same MS subjects using a 3T MAGNETOM Vida system. Fast SWI-EPI provides similar visualization of CVS and PRL as SWI-GRE. Filtered phase images are displayed with inverted contrast (right-handed convention).



3 Head-to-head comparison of T2*-weighted 3D EPI magnitude images without and with acceleration and DL reconstruction (Protocol C) acquired in the same MS patient using a 3T MAGNETOM Vida system. Both sets of images display CVS in a similar way (red arrows).



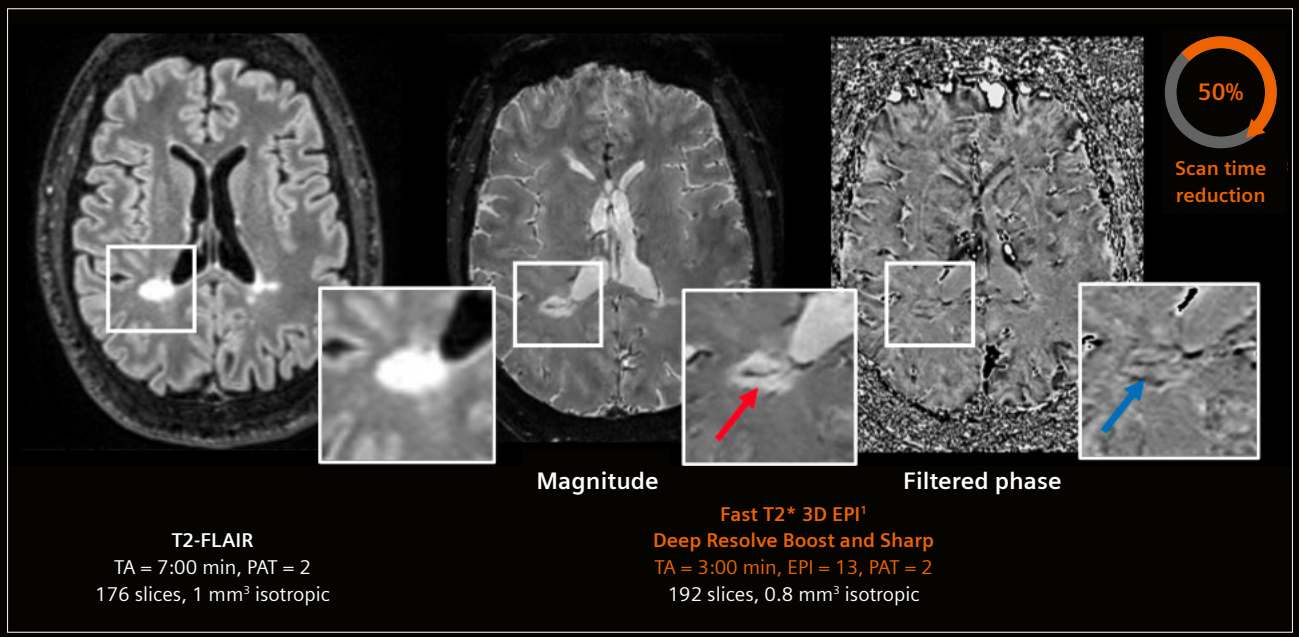
4 Multiplanar view of brain images acquired with Fast T2*-weighted 3D EPI magnitude images (Protocol C). High isotropic resolution (0.65 mm) enables clear visualization of CVS in all imaging planes (red arrows).



Standard T2* 3D EPI
TA = 5:40 min, EPI = 17, No PAT
256 slices, 0.65 mm³ isotropic

Fast T2* 3D EPI[1]
Deep Resolve Boost and Sharp
TA = 1:30 min, EPI = 17, PAT = 4
256 slices, 0.65 mm³ isotropic

5 Head-to-head comparison of filtered phase 3D EPI images without and with acceleration and DL reconstruction (Protocol C) acquired in the same MS patient using a 3T MAGNETOM Vida system. Both sets of images display PRL in a similar way (blue arrows). Filtered phase images are displayed with inverted contrast (right-handed convention).



T2-FLAIR
TA = 7:00 min, PAT = 2
176 slices, 1 mm³ isotropic

Fast T2* 3D EPI[1]
Deep Resolve Boost and Sharp
TA = 3:00 min, EPI = 13, PAT = 2
192 slices, 0.8 mm³ isotropic

6 Fast T2*-weighted 3D EPI images (Protocol D) from a patient with MS acquired on a 1.5T MAGNETOM Sola using GRAPPA (R = 2) with Deep Resolve Boost and Deep Resolve Sharp. Both Central Vein Sign (CVS) and Paramagnetic Rim Lesion (PRL) can be clearly visualized in the same T2-hyperintense lesion, as shown on the corresponding magnitude image (red arrow) and filtered phase image (blue arrow). Filtered phase images are displayed with inverted contrast (right-handed convention).

Protocol C: Fast submillimeter T2*-weighted 3D EPI with PI and DL reconstruction at 3T

Recent technical studies have demonstrated that highly accelerated 3D EPI combining advanced undersampling with DL-based denoising enables rapid, high-resolution T2*-weighted brain imaging [10, 11]. Building on this approach, we accelerated submillimeter T2*-weighted 3D EPI using CAIPIRINHA (2 × 2, shift = 1) [12] and Deep Resolve reconstruction (DRB and DRS) to improve image quality. This combination reduced the acquisition time to 1:30 minute (74% reduction) compared to the standard 5:40 minutes for the 3D EPI protocol while preserving the image quality necessary for CVS detection (Fig. 3). Note that fast T2*-weighted 3D EPI allows multiplanar visualization of the CVS for increased diagnostic confidence (Fig. 4). Additionally, filtered phase images from the fast T2*-weighted 3D EPI remained comparable to the standard T2*-weighted 3D EPI, thus allowing simultaneous detection of PRL (Fig. 5).

Protocol D: Fast submillimeter T2*-weighted 3D EPI with PI and DL reconstruction at 1.5T

The technical advantages of accelerated submillimeter T2*-weighted 3D EPI demonstrated at 3T can also be extended to 1.5T. Note that longer TE and TR values are required to provide sufficient T2* weighting at 1.5T. Consequently, a standard 0.8 mm isotropic T2*-weighted 3D EPI acquisition with an EPI factor of 13 requires approximately 6 minutes. An accelerated 3D EPI version with GRAPPA (R = 2) and Deep Resolve (DRB and DRS) reconstruction can reduce the scan by 50% (3-minute scan) and preserve structural details. Both CVS and PRL can be clearly visualized on the 3-minute 3D EPI scan (Fig. 6).

Discussion and conclusions

The growing role of MRI in MS diagnosis increases the need for fast, high-quality brain MRI. Given that CVS and PRL are now part of the diagnostic criteria of MS, this need is even more urgent for the implementation of susceptibility-sensitive MRI sequences into routine diagnostic MRI evaluation for MS [4]. The four protocols presented in this article highlight the potential of next-generation susceptibility MRI sequences for faster diagnostic imaging workflows in MS. By combining 3D EPI readout, parallel imaging, and deep-learning reconstruction, these new techniques substantially shorten acquisition times while preserving the visualization of CVS and PRL. Overall, these protocols achieved a 50%–75% reduction in scan time, thus supporting the feasibility of adding high-resolution susceptibility MRI to any diagnostic imaging workflow and enabling users to select the protocol best suited to their clinical setting. Ultimately, these shorter scans will also improve patient comfort, reduce sensitivity to motion, and increase overall scanning efficiency.

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